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CONTAMINANT MANAGEMENT STRATEGIES FOR THE GREAT LAKES: OPTIMAL SOLUTIONS UNDER UNCERTAIN CONDITIONS

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ABSTRACT. Optimization, uncertainty analysis, and mass balance modeling techniques were combined into a framework that can help decision makers identify cost-effective load reduction methods for achieving acceptable contaminant concentrations in the Great Lakes. The utility of the framework is demonstrated by deriving an optimal phosphorus load reduction plan for the Great Lakes. An optimal plan is defined as the least-cost approach that can achieve desired phosphorus concentrations in all Great Lakes basins under realistic, stochastic phosphorus loading and settling rates. The analysis suggests that implementation of phosphorus load reduction measures recommended in the U. S. - Canadian 1978 Great Lakes Water Quality Agreement, its 1983 supplement, and other plans that do not account for environmental uncertainty may by sub-optimal. Compared with the load reduction strategies of the 1978 Water Quality Agreement and its supplement, implementation of the optimized load reduction strategy would lead to substantial annual cost savings and an increased probability of achieving desired phosphorus concentrations. Results emphasize the importance of quantitatively accounting for environmental uncertainty in management models.
ADDITIONAL INDEX WORDS: Optimization, phosphorus, cost/benefit analysis, Monte Carlo method, management planning, mathematical models.

INTRODUCTION

Management of the Great Lakes is a complex and formidable task. Decision makers in government and private institutions are confronted with multiple goals, often conflicting, from which they must try to achieve fair and balanced policies. Management goals for the Great Lakes include enhancement of commercial and sports fisheries, attainment of desired water quality, rational consumptive use and diversions of lake water, and sensible use of the lakes for transportation, recreation, mining, hydropower, and waste disposal. In complex systems such as the Great Lakes, the pursuit of one goal can often affect the outcome of others, sometimes in non-intuitive ways. Mathematical models that can simultaneously consider many goals provide a method for optimizing resource allocation in such a complex system. Construction of such models should be a high priority for Great Lakes decision makers. As Kasten (1985) remarked, "We can no longer take a piecemeal approach to management that sees the resource from a limited geographical, disciplinary or political point of view."

Management decisions are made in an uncertain environment. Decision makers do not know what conditions will exist in the years following their decisions nor how these conditions will affect the impact of their decisions. While uncertainty complicates decision making, there are techniques for guiding decision makers toward the most informed decisions possible. Whether applied to optimization models (e.g., Fisher 1983) or contaminant fate and behavior models (e.g., O'Neill *et al.* 1982), these techniques quantify uncertainty in model parameters and inputs, suggest where resources should be allocated in order to decrease sources of uncertainty, and pinpoint those decisions that have the highest probability of achieving desired goals.

In this paper an optimization-uncertainty analysis modeling framework is presented that can be used to address multi-objective problems such as those facing Great Lakes decision makers. To demonstrate the utility of the framework, the relative cost effectiveness of several Great Lakes phosphorus management strategies was examined. Phosphorus management strategies from the U. S. - Canadian 1978 Water Quality Agreement (International Joint Commission 1978) and its 1983 supplement (International Joint Commission 1983) were compared with alternative strategies derived from the optimization-uncertainty analysis model. The analysis demonstrated that the success of a management strategy depends greatly on whether or not uncertainty (e.g., year-to-year variability in Great Lakes phosphorus loading and settling rates) is quantitatively accounted for in the assessment procedure. Great Lakes phosphorus management strategies that only consider average loads and conditions were not found to be appropriate for guiding management decisions. Therefore, an overall recommendation from this analysis is that models designed for aiding Great Lakes management should be subjected to an uncertainty (and optimization, where possible) analysis. By doing so, the implications of management decisions will be more fully understood before the decisions become operational.

The Model

Background

Our modeling framework was synthesized from earlier work of Chapra and Sonzogni (1979), Chapra *et al.* (1983), and Lesht (1985). Chapra and Sonzogni (1979) developed an eleven basin, linear equation, phosphorus mass balance model for the Great Lakes. It can be used to predict the steady state concentration of total phosphorus in each of the basins for a given loading to any of the basins. The salient features of their model are: phosphorus may be advected to downstream basins, mixed between adjacent basins, or removed from basins via settling. In their model, as well as ours, basins are segmented as shown in Figure 1; all basins are considered completely mixed. The same set of linear mass balance equations were used in a linear programming, non-stochastic (i.e., no uncertainty), optimization model (Chapra *et al.* 1983). The purpose of this model was to compute basin-wide, least cost methods for achieving desired phosphorus concentrations (Table 1) in each of the eleven basins. Their work indicated that "An optimal phosphorus management strategy for the Great Lakes should include both point and diffuse source controls, and zoned rather than uniform treatment." An important implication of their work was that requiring uniform phosphorus control measures across all basins might not be the most cost-effective method for achieving desired phosphorus concentrations.

The phosphorus mass balance model of Chapra and Sonzogni (1979) was modified by Lesht (1985) to accept time-varying phosphorus inputs and time-varying "apparent" settling rates. Accomodations for time-varying settling rates were made to examine the consequences of Rodgers and Salisbury's (1981) conclusion that, in Lake Michigan, "apparent" particle settling rates are positively correlated with the extent of lake ice cover. Incorporating these features, Lesht (1985) tested the time-dependent model with hypothesized settling rates and actual loading data for the period 1976 through 1982. His results compared favorably with data collected during this period in Lakes Erie, Ontario, and Michigan and support the utility of a time-dependent mass balance approach for examining Great Lakes contaminant dynamics.

Approach

The steady-state optimization model of Chapra *et al.* (1983) and Lesht's (1985) time-dependent mass balance model were each augmented with a Monte Carlo routine that introduces stochastic phosphorus loading and settling rates into simulations. The optimization model was used to determine a cost-effective Great Lakes phosphorus management strategy that would achieve desired phosphorus concentrations under stochastic loading and settling conditions. A "strategy" consists of a combination of various levels of basin-specific point and diffuse loading controls (Table 2). Once

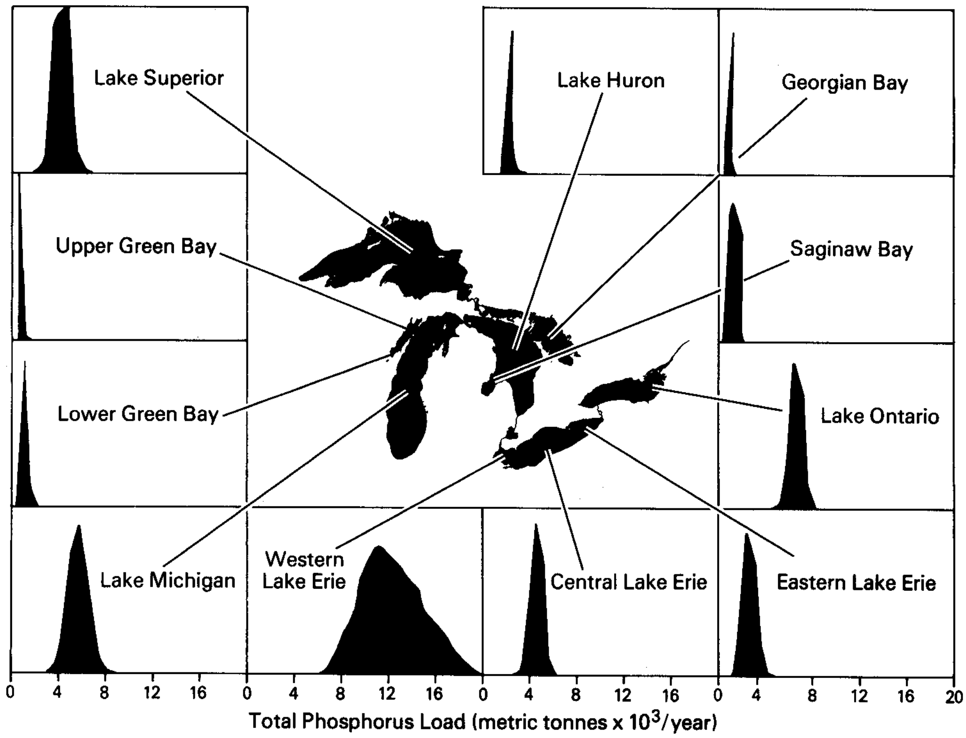

FIG. 1. Model segmentation and phosphorus loading probability density functions (unit area) used in analyses. Loads with greatest variability are widest along the abcissa.

an optimal strategy was identified, the time-dependent model was used to compare the ability of this strategy to attain desired phosphorus concentrations under uncertain conditions with that of present or proposed treatment strategies (Table 3). This was done by applying the load reduction techniques specified by each strategy to identical time-series of uncertain loading and settling conditions. Using this Monte Carlo approach, the probability of a treatment strategy leading to desired phosphorus concentrations could be estimated. Furthermore, the approach made it possible to determine if the strategies differ statistically in their effectiveness.

TABLE 1. Desired phosphorus concentrations in Great Lakes basins[a]

Basin	Suggested Objective (μg/L)[b]
Superior	5
Lower Green Bay	15
Upper Green Bay	10
Michigan	7
Georgian Bay	5
Saginaw Bay	15
Huron	5
Western Lake Erie	15
Central Lake Erie	10
Eastern Lake Erie	10
Ontario	10

[a]Phosphorus Management Strategies Task Force (1980)
[b]$PCHG_i$ in eq. 2 calculated with this information.

The equations used to predict steady-state (for optimization purposes) and time-dependent phosphorus responses of the eleven basins have been well documented in Chapra and Sonzogni (1979) and Lesht (1985), respectively. The reader is referred to these papers for details. Only one difference exists between the present formulation and theirs: here, their "W_n" term (which denotes total phosphorus loads to each of n basins) is divided into atmospheric, point, diffuse rural, and diffuse urban components. This division was required by our optimization scheme and was based on Table 3 in Chapra *et al.* (1983).

TABLE 2. Unit cost of point and non-point source measures to reduce total phosphorus loadings [a].

Treatment	Explanation	Annual cost ($$10^6$ per 1,000 MT Reduction)
Municipal Point Sources		
Stage 1	Municipal wastewater effluent = 1.0 mgTP/L	3.5
Stage 2	Effluent concentration reduced from 1.0 to .5 mgTP/L	8.9
Stage 3	Effluent concentration reduced from .5 to .3 mgTP/L	121.0
Rural Runoff		
Stage 1	Voluntary, low cost land management practices	1.7
Stage 2	Con. tillage, terracing, crop rotations, and strip crops	51.5
Stage 3	Cover crops, critical area seeding, runoff control	306.0
Urban Runoff		
Stage 1	Pollutant reduction at source, vacuum street sweeping	124.0
Stage 2	Detention and sedimentation	258.0

[a]Differences with cost figures from Chapra *et al.* (1983) represent updated information (U.S. Army Corps of Engineers 1982).

TABLE 3. Phosphorus load reduction strategies that were examined under stochastic phosphorus loading and settling conditions.

Strategy Label	Explanation
1970	No additional treatment capacity over mid-1970s levels.
AVEOPT	Optimal treatment capacities calculated for non-stochastic conditions
1978	Treatment capacities specified by original 1978 agreement
1983a	1978 agreement plus level 1 nonpoint source controls in all 11 basins
1983b	1978 agreement plus levels 1 and 2 nonpoint source controls in all 11 basins
96	Optimal treatment capacities calculated for stochastic conditions (96th percentile solution)
97	Optimal treatment capacities calculated for stochastic conditions (97th percentile solution)
98	Optimal treatment capacities calculated for stochastic conditions (98th percentile solution)
99	Optimal treatment capacities calculated for stochastic conditions (99th percentile solution)

Monte Carlo Routine

In the Monte Carlo algorithm, new loading and settling rate values were picked randomly from pre-specified truncated normal distributions for each simulation year. The assumed phosphorus loading distributions (Fig. 1) were defined in part by statistical information on recent loading data (Table 4). Distributions were truncated by limiting possible loading values to a range within .5X and 2X of their mean value. These truncations seemed appropriate given historical data and eliminated

TABLE 4. Great Lakes phosphorus loading (1986–1982).

Basin	Ave. P load (MT/yr)[a]	CV[b] (%)
Superior	4,657	34.2
Lower Green Bay	972	24.9
Upper Green Bay	171	24.8
Michigan	4,390	31.1
Georgian Bay	749	18.0
Saginaw Bay	1,221	18.0
Huron	1,970	18.0
Western Lake Erie	7,361	52.2
Central Lake Erie	4,707	21.2
Eastern Lake Erie	1,407	46.4
Ontario	5,800	13.1

[a]Phosphorus loading statistics derived from Lesht (1985).
[b]Coefficient of variation.

the possibility of an unrealistic loading value being used in calculations. In picking loading values, no correlation of point and diffuse loads across basins or within lakes was assumed.

Probability distributions for within-basin settling rates were defined by using apparent settling rates (Chapra and Sonzogni 1979) as mean values and coefficients of variations of 50 percent in all cases. The 50 percent figure was chosen somewhat arbitrarily but is not thought to be unreasonable. Test case results of the optimization analysis showed that costs of optimal load reductions were twice as sensitive to loading variability as they were to settling variability. The range of possible settling rates was constrained between .75X and 3X of their mean values. Settling rate changes were assumed to be correlated across basins since the extent of winter ice cover on all lakes is positively correlated (see Fig. 15 in Assel *et al.* 1983). It was also assumed that lake levels are relatively constant, and that uncertainty associated with mixing and advection between adjacent basins has minimal impact on whole lake phosphorus concentrations.

Optimization Problem

As in Chapra *et al.* (1983), the objective of the optimization problem is to minimize the total annual cost of achieving desired phosphorus concentrations by selecting appropriate combinations of load reduction capacities:

$$\text{MIN. } Z = \sum_{i=1,}^{11} \left\{ \sum_{k=1}^{MP} CP_k * RP_{k,i} + \sum_{n=1}^{MR} CR_n * RR_{n,i} + \sum_{m=1}^{MU} CU_m * RU_{m,i} \right\} \quad (1)$$

where,

Z = total annual cost for achieving the desired water quality objectives,

MP = number of stages for controlling loadings from municipal point sources,

MR = number of stages for controlling loadings from rural runoff,

MU = number of stages for controlling loadings from urban runoff,

CP_k = annual cost per unit reduction (Table 2) in the total phosphorus load due to stage k control of municipal point sources,

$RP_{k,i}$ = load reduction attributable to stage k control of municipal point sources in lake basin i,

CR_n = annual cost per unit reduction (Table 2) in the total phosphorus load due to stage n control of rural runoff,

$RR_{n,i}$ = load reduction attributable to stage n control of rural runoff in lake basin i,

CU_m = annual cost per unit reduction (Table 2) in the total phosphorus load due to stage m control of urban runoff, and

$RU_{m,i}$ = load reduction attributable to stage m control of urban runoff in lake basin i.

Reduction of atmospheric sources of phosphorus loading is not considered in the model.

As in Chapra *et al.* (1983), the constraints for this problem fall into two classes: (a) total phosphorus loading must be reduced sufficiently to achieve desired phosphorus concentrations (at steady-state) in all basins; (b) a required reduction in load cannot exceed a facility's capacity for that reduction. The equations used to describe these constraints are:

$$\sum_{j=1}^{11} \left\{ R_{i,j} * TR_j \right\} \geq PCHG_i \quad (2)$$

where,

$R_{i,j}$ = change in the average, whole-basin total phosphorus concentration in basin i (μg/L) resulting from a 1,000 MT/y change in the total phosphorus load to basin j,

TR_j = total load reduction (1,000 MT/y) to basin j, and

$PCHG_i$ = required reduction in average total phosphorus concentration (μg/L) for basin i to achieve its desired concentration (Table 1).

$$R_{t,s,i} \leq RMAX_{t,s,i} \quad (3)$$

where,

$R_{t,s,i}$ = total phosphorus load reduction (1,000 MT/y) attributable to stage t control of source s in basin i, and

$RMAX_{t,s,i}$ = maximum total phosphorus load reduction (1,000 MT/y) that can be achieved through stage t control of source s in basin i.

Because the total loading term was subdivided into its component parts, an additional constraint needed explicit definition in the model: if the input from a component of the total load is less than the capacity which exists to treat it, then the amount of treatment used cannot exceed the load. Mathematically,

$$R_{t,s,i} \leq W_{s,i} \quad (4)$$

where,

$R_{t,s,i}$ = defined as before, and

$W_{s,i}$ = the loading of total phosphorus via source s to basin i.

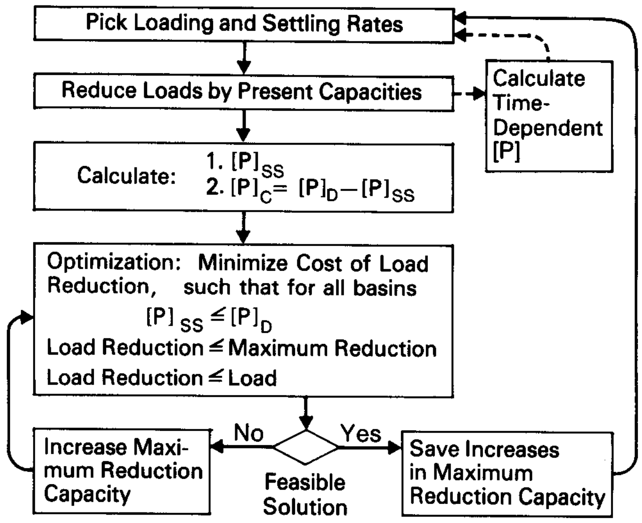

FIG. 2. Algorithm for determining optimal phosphorus management strategy under stochastic conditions. Keys to phosphorus concentration term, [P], subscripts: "SS," steady state; "C," change required in order to achieve steady state; "D," desired concentration. The dashed line indicates the computational path used to compare the nine phosphorus management strategies that were tested in this analysis.

Computational Scheme

In order to define optimal phosphorus treatment strategies for stochastic phosphorus input and removal rates, an algorithm (Fig. 2) using equations 1–4 was devised. The algorithm determines the lowest cost combination of point and diffuse treatment capacities needed in each basin to achieve desired phosphorus concentration in all basins under uncertain conditions. This lowest cost set of treatment capacities was formed by running the model in the Monte Carlo mode so that a large number of loading and settling rate time series could be considered. Two major loops governed the sequence of computations: the number of Monte Carlo passes (n = 100) and the number of consecutively different loading and settling scenarios (n = 30) within each Monte Carlo pass. The total number of iterations (n = 3,000) ensured that a representative sample of randomly sequenced values were chosen from each loading and settling rate distribution. For each loading and settling rate scenario picked by the Monte Carlo algorithm, steady-state phosphorus concentrations of the eleven basins were calculated using the Chapra and Sonzogni (1979) model. Before calculating steady-state concentrations, phosphorus loads were adjusted downward to account for any treatment capacity already in effect. Because different settling rates were used in each scenario it was necessary to recalculate the $[A]^{-1}$ matrix (sensu eq. 7 of Chapra and Sonzogni 1979; eq. 4 of Lesht 1985) for each scenario. Resulting steady-state phosphorus concentrations were compared with desired, basin-specific phosphorus concentrations. The difference between these concentrations represented the amount by which steady-state phosphorus concentrations had to be reduced to meet target concentrations. This difference was entered as $PCHG_i$ in eq. 2, above. Minimization of the objective function (eq. 1) was carried out (subroutine ZX3LP, International Mathematical and Statistical Libraries, Inc., 1984) subject to the constraints in eqs. 2–4. If a feasible solution was obtained, recommended treatment capacities were retained for later analysis. If no feasible solution existed then one of the following had to occur for the program to continue: (a) desired phosphorus concentrations had to be relaxed, or (b), more capacity for reducing phosphorus inputs had to be added. Option (b) was selected for the purposes of this investigation since it seemed unlikely that option (a) would be acceptable in the Great Lakes community (although examination of tradeoffs between (a) and (b) might be desirable at some later time). Accordingly, the program would increase all of the possible treatment capacities by a small factor, return to the optimization routine, and repeat this sequence until convergence on an optimal set of treatment strategies occurred. Only those increases in treatment capacity which were needed to attain an optimal solution were kept (i.e., corresponding $RMAX_{t,s,i}$ values are permanently increased in eq. 3); all others were reduced to the values they had at the beginning of the scenario's optimization process. Thus, as more and more of the 30 loading and settling scenarios were considered in the simulation, treatment capacities ($RMAX_{t,s,i}$) increased in order to handle loads that previous treatment capacities could not. Increases in treatment capacities were always available to apply against new loading scenarios although they were not necessarily utilized in new optimal solutions. The entire sequence was repeated until the two major loops were completed. At the beginning of each 30-scenario iteration, maximum treatment capacities ($RMAX_{t,s,i}$) were initialized at the maximum reductions specified by Table 5 in Chapra *et al.* (1983). Because of the iterative nature of the Monte Carlo approach, a statistical distribution of optimal treatment capacities was generated for each year, basin, and treatment type. These distributions form the basis of the optimized treatment strategies examined below.

RESULTS AND DISCUSSION

Identification of Optimal Management Strategies

Three thousand sets of optimal load reduction plans were identified as a result of the combined optimization-uncertainty analysis approach. Each set contains a basin-specific recommendation for point, rural, and urban runoff treatment capacities that lead to desired phosphorus concentrations in all basins for the loading and settling rate scenario considered. Expressed differently, 3,000 optimal load reduction capacities were identified for each type of treatment (n = 8, Table 2) in each basin (n = 11). Hence, 88 separate statistical distributions of treatment capacities could be formed from the 3,000 sets of optimal load reduction plans. Individual sets of 88 treatment capacities from the same percentile of their respective distributions were sought: (a) whose effectiveness in attaining desired concentrations in all basins (as defined by a metric of total system improvement sensu Chapra *et al.* 1983) was equal to or greater than the effectiveness of treatments required by the 1978 Great Lakes Water Quality agreement or its supplement and (b) whose costs were equal or less than treatments required by the 1978 agreement or its 1983 supplement. Four sets of 88 treatment capacities, corresponding to the 96th to the 99th percentile of optimal treatment distributions (hereafter referred to as strategies "96," "97," "98," and "99"), met both requirements. Capacities corresponding to the 100th percentile did not meet the cost requirements, however, and support the earlier findings of Chapra *et al.* (1983), that there is a point at which increases in load reduction expenditures do not significantly increase the probability of achieving target concentrations (Fig. 3).

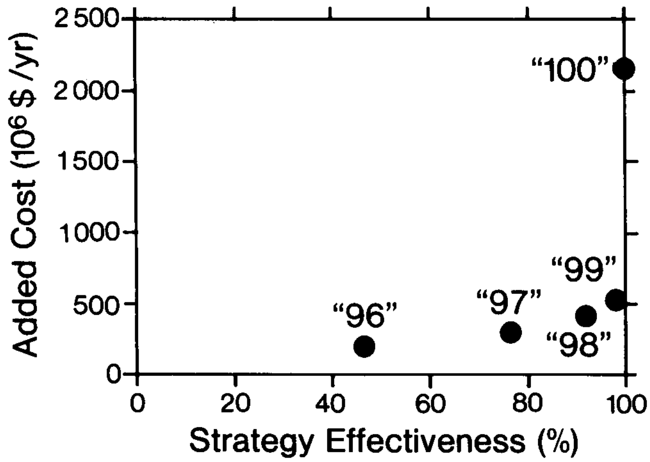

FIG. 3. Probability and cost of achieving target phosphorus concentrations in all basins: results from optimization analysis. Basin-specific probabilities associated with each strategy were weighted using the method of Chapra et al. *(1983) in order to calculate a metric of total system improvement attributable to each load reduction strategy.*

Comparison of Management Strategies

The management strategies that were compared (Table 3) correspond to phosphorus load reduction capacities recommended in the 1978 agreement ("1978"), its 1983 supplement ("1983a," "1983b"), and capacities calculated through the use of optimization procedures ("96" - "99" and "AVEOPT"). Treatment capacities recommended in strategy AVEOPT were calculated using the optimization program discussed previously but resulted from consideration of average loading and average settling rates only. This type of optimization analysis in which uncertainty is not considered is the type of analysis described in Chapra *et al.* (1983). The probability of a strategy achieving desired phosphorus concentrations under uncertain conditions was determined by programming a strategy's load reduction capacities (Appendix A, Table A-1) into the time-dependent model of Lesht (1985), running the model through 100 30-year time series of stochastic loading and settling rates, and then comparing predicted concentrations against desired concentrations on a basin-by-basin basis. The predicted concentrations that were used in the latter comparisons were those that occurred after the onset of constant, average phosphorus concentrations in simulations. For example, constant average phosphorus concentrations occurred in Lake Ontario after 10 simulation years. Between simulation years 11 and 30, 2,000 individual predictions of Lake Ontario phosphorus concentration were generated (100 iterations × 20 years). Implementation of phosphorus reduction measures recommended by the 1978 agreement led to 1,140 of these 2,000 predicted concentrations that were less than or equal to the target concentration for Lake Ontario. Therefore, the probability that the 1978 agreement would successfully achieve the desired concentration in Lake Ontario is 57 percent.

The probability of successfully achieving desired concentrations varied greatly among reduction strategies (Table 5). Two of the eleven basins (Superior and Georgian Bay) already had a 100 percent probability of achieving desired phosphorus levels without additional phosphorus reductions to any of the basins (strategy "1970"). Implementation of treatment capacities recommended in strategy "1978" improved the probability of achieving desired concentrations in the nine remaining basins. However, in four of these nine basins (lower Green Bay, Saginaw Bay, western and central Lake Erie) there was still less than a 50 percent probability of achieving desired phosphorus levels when stochastic conditions were considered. The probability of success in eastern Lake Erie and Lake Ontario was slightly less than 60 percent for strategy "1978." Additional load reductions recommended by strategy "1983a" greatly improved the probability of achieving desired phosphorus concentrations in Lake Ontario and, to a lesser extent, in the basins of Lake Erie and Green Bay. Further control of diffuse rural and urban loading sources by strategy "1983b," led to significant improvements in lower Green Bay, and to a lesser degree, in upper Green Bay and Saginaw Bay. Compared with strategy "1983b," optimized strategies "98" and "99" had a higher probability of achieving desired phosphorus concentrations in all basins. Strategies "96" and "97" were somewhat less successful. The success of strategy "AVEOPT" was comparable to that of strategy "1978," but less so than strategies "97"-"99" that were explicitly formulated for stochastic conditions.

The relative probabilities of success for the various management options can be demonstrated by graphing the probability density functions of predicted phosphorus concentrations that result from implementation of each strategy: examples are shown for Lake Michigan and Lake Ontario (Fig. 4). Data used to form probability density functions were the numerous individual predictions of phosphorus concentrations for the period following establishment of constant mean phosphorus concentrations. Treatment strategies that were least able to minimize the effects of uncertain loading and settling rates have density functions that range widely along the abscissa. For example, the predicted range of possible phosphorus concentrations in Lake Ontario is about 10 μg/L for strategy "1970" but only 4 μg/L for strategy "99." The range of possible concentrations for strategy "99" is not only less than that of other strategies but is also shifted more toward lower concentrations than those of other treatment strategies. The management implication of adopting a strategy that has been developed explicitly for stochastic conditions (e.g., "99") is that phosphorus concentrations will vary less and will be less likely to exceed desired concentrations than concentrations that result from other strategies.

The amount of overlap among density functions varies from basin to basin. In all basins, average constant phosphorus concentrations resulting from implementation of the 1978 agreement were statistically different from those which would have been expected with no additional treatment over mid-1970s levels (Table 6). Enhancements to the load reduction capacities of strategy "1978" by strategies "1983a" and "1983b" brought about statistically significant improvements in the steady-state phosphorus concentrations of basins in which load reduction enhancements were made. For

TABLE 5. Probability of achieving desired phosphorus concentrations for various phosphorus management strategies.

Basin	Strategy 1970	1978	1983a	1983b	96	97	98	99	AVEOPT
Superior	100	100	100	100	100	100	100	100	100
Lower Green Bay	0	8	19	54	25	53	78	92	41
Upper Green Bay	14	72	89	99	92	99	100	100	96
Michigan	61	100	100	100	100	100	100	100	96
Georgian Bay	100	100	100	100	100	100	100	100	100
Saginaw Bay	0	5	14	34	22	56	90	99	28
Huron	88	100	100	100	100	100	100	100	100
Western Erie	0	15	26	26	40	66	86	96	12
Central Erie	2	46	61	61	62	85	97	100	40
Eastern Erie	8	55	66	66	72	90	99	100	46
Ontario	0	57	97	97	40	90	100	100	48

instance, the improvements in lower Green Bay phosphorus concentrations that result from progressive implementation of strategies "1978," "1983a," and "1983b" are statistically distinguishable from each other. Similarly, phosphorus concentrations in Lakes Erie and Ontario significantly improved with the implementation of enhancements to strategy "1978" by strategy "1983a." No further improvements in Lakes Erie and Ontario phosphorus concentrations resulted from implementation by strategy "1983b" since this strategy did not specify increased load reductions in these basins (see Appendix A). Mean phosphorus concentrations resulting from optimized strategies "99" and "98" were always statistically different from each other as well as from all other strategies. Application of these strategies consistently resulted in lowest phosphorus concentrations in all basins. In all basins but Lake Ontario, phosphorus concentrations resulting from strategy "97" were equal to or less than those resulting from strategy "1983b." In many basins, phosphorus concentrations resulting from implementation of strategy "AVEOPT" were statistically greater than those resulting from implementation of most other strategies.

To measure overall system performance of the various load reduction strategies, simulation results were analyzed using the "metric of total system improvement" approach of Chapra *et al.* (1983; p. 86). In all but one case, treatment capacities corresponding to strategies "96" through "99" were more effective in achieving target phosphorus levels than were capacities recommended in other strategies (Fig. 5). In addition, annual costs associated with strategies "96" through "99" were generally less than costs associated with strategies "1978," "1983a," and "1983b." Optimized treatment capacities calculated for average loading and settling conditions (AVEOPT) were, by definition, 100 percent effective in attaining desired phosphorus concentrations under non-stochastic conditions. However, when the effectiveness of "AVEOPT" was tested under realistic, stochastic conditions it performed poorly. This is because strategy "AVEOPT" was formed by considering only one of many probable loading and settling scenarios. Optimal treatment strategies that were calculated for stochastic conditions had much greater success than "AVEOPT" in attaining target phosphorus levels. The drop in the effectiveness of strategy "AVEOPT" with stochastic conditions emphasizes the need for explicit inclusion of uncertainty into management models.

Recommended Changes in Treatment Strategy

The placement, type, and intensity of phosphorus load reduction capacity calculated by the optimization procedure differs from that recommended in the 1978 Great Lakes Water Quality Agreement (strategy "1978" and its 1983 supplement, strategies "1983a" and "1983b") (Figs. 6–8; for clarity, comparisons are made with optimal strategy "99" only). Relative to strategy "1978," strategy "99" calls for increased point source primary treatment capacity in ten of eleven basins (Fig. 6). The largest recommended increase is 4,000 MT/y in western Lake Erie. This recommendation

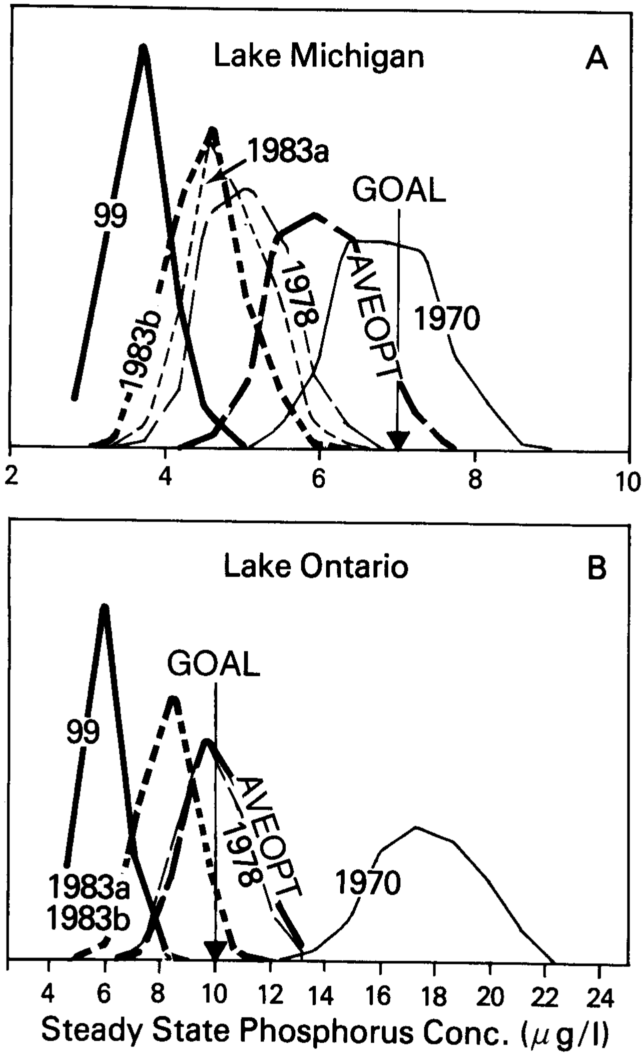

FIG. 4. Probability density functions (unit area) of phosphorus concentrations that result from implementation of management strategies listed in Table 3 (strategy labels appear on lines; results for Lakes Michigan and Ontario are representative of the responses of other basins). For clarity, results from strategies "98," "97," and "96" are not shown. For all strategies, average times to onset of constant mean concentrations were: Superior, 30 y; Lower Green Bay, 2 y; Upper Green Bay, 7.5 y; Michigan, 15 y; Georgian Bay, 10 y; Saginaw Bay, 1 y; Huron, 16 y; Western Lake Erie, 1 y; Central Lake Erie, 2 y; Eastern Lake Erie, 2 y; Ontario, 10 y.

is twice that recommended in strategies "1983a" and "1983b." Other significant increases in primary point source reduction capacity are recommended by strategy "99" for Lakes Michigan and Ontario. The latter increase in Lake Ontario point source reduction was also recommended by strategies "1983a" and "1983b." Secondary point source reduction in central Lake Erie and Lake Ontario is deemphasized by strategy "99." However, a slight increase is called for in lower Green Bay. Increased capacity for controlling inputs of phosphorus from rural runoff are recommended for all basins, but particularly Lakes Erie and Ontario (Fig. 7). Recommendations are primarily for increased voluntary land management practices (stage 1 controls; see Table 2) but in western Lake Erie more intensive (stage 2) rural runoff controls are recommended too. Strategy "99" also recommends that increased capacity for controlling phosphorus inputs from urban runoff is needed in most basins (Fig. 8). This was particularly true for western Lake Erie. In lower Green Bay and Saginaw Bay, the need for additional stage one urban runoff controls that was specified by strategies "1983a" and "1983b" is confirmed by the optimization analysis. However, an excess (e.g., Lake Michigan) or deficit (e.g., western Lake Erie) of urban runoff controls is recommended by strategies "1978," "1983a," or "1983b" for other basins. The intensity and spatial arrangement of treatment capacities recommended by the optimization analysis is needed in order to maintain desired average phosphorus levels in all basins for the least cost. However, the cost and effectiveness of load reduction techniques can vary, so recommendations from the optimization analysis might also be subject to some variation. Nevertheless, the stage-specific costs of a particular treatment type (e.g., primary, secondary and tertiary stages of point source treatment) are quite different from each other. This makes it unlikely that the basic recommendations of the optimization analysis would change significantly since the robustness of optimal treatment selection is proportional to the magnitude of cost differences between stages of a treatment. If basins were not connected and could be managed solely for themselves, recommended reduction capacities would most likely differ from those proposed by the optimization analysis.

Looking Forward

Our analyses suggest that future approaches to Great Lakes contaminant management should quantitatively recognize the importance of real world uncertainty. By doing so it should be possible to determine, *a priori*, whether various management approaches are likely to produce statisti-

TABLE 6. Comparison of steady-state phosphorus concentrations resulting from implementation of phosphorus management strategies.

Basin	Strategies not Significantly Different (Underlined)[a]								
Superior	1970	AVEOPT	1978	1983a	1983b	96	97	98	99
Lower Green Bay	1970	1978	1983a	96	AVEOPT	97	1983b	98	99
Upper Green Bay	1970	1978	1983a	96	AVEOPT	1983b	97	98	99
Michigan	1970	AVEOPT	96	1978	1983a	97	1983b	98	99
Georgian Bay	1970	AVEOPT	1978	96	1983a	1983b	97	98	99
Saginaw Bay	1970	1978	1983a	96	AVEOPT	1983b	97	98	99
Huron	1970	AVEOPT	1978	1983a	96	1983b	97	98	99
Western Erie	1970	1978	AVEOPT	1983a	1983b	96	97	98	99
Central Erie	1970	AVEOPT	1978	1983a	1983b	96	97	98	99
Eastern Erie	1970	AVEOPT	1978	1983a	1983b	96	97	98	99
Ontario	1970	96	AVEOPT	1978	97	1983a	1983b	98	99

[a]Underlined treatments (see Table 3 for descriptions) do not yield significantly different phosphorus concentrations (ALPHA = .05). The multiple range tests used to compare mean effects were options DUNCAN, WALLER, and REGWQ of PROC ANOVA of SAS (SAS Institute Inc. 1985). All tests gave similar results. Order of strategies reflects decreasing mean values from left to right.

cally distinguishable results. Analyses such as these may support arguments that one combination of load reduction treatments is just as effective as another, even if they are quite different in cost and application. Our analyses further suggest that a coupled optimization and uncertainty analysis approach will be most useful in determining the most cost effective (and most likely to succeed) method of contaminant treatment. Coupled optimization and uncertainty analysis techniques provide more useful information than traditional management modeling frameworks. Information such as shown in Figure 5 can be used to pinpoint the amount of funding that is needed in order to guarantee a desired probability of success. Alternatively, if expenditure levels are fixed, the infor-

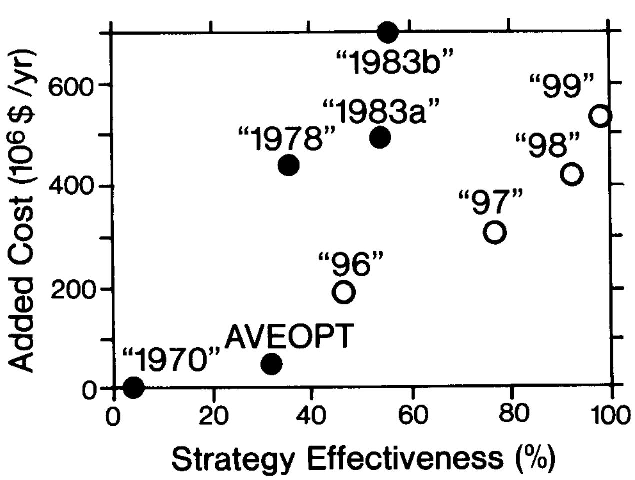

FIG. 5. Probability and cost of achieving target phosphorus concentrations in all basins: comparison of all strategies tested. Basin-specific probabilities from Table 5 were weighted using the method of Chapra et al. *(1983) in order to calculate a metric of total system improvement attributable to each load reduction strategy.*

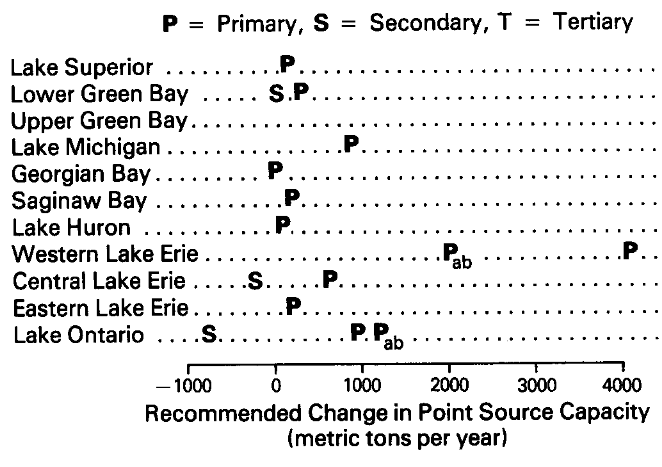

FIG. 6. Changes in point source treatment capacities recommended by strategies "99," "1983a," and "1983b" relative to those recommended in the 1978 agreement (zero line). Unsubscripted "P, S and T" represent strategy "99"; otherwise, subscript "a" represents strategy "1983a," "b" represents strategy "1983b," and "ab" represents identical recommendations from strategies "1983a" and "1983b." If a strategy is not shown on the graph, then little or no change in strategy "1978" capacities was recommended.

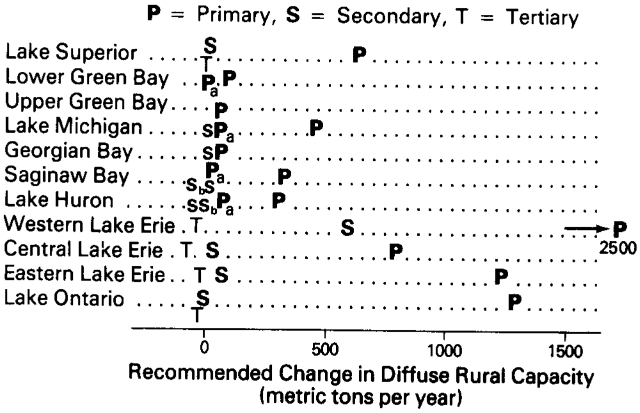

FIG. 7. Changes in diffuse rural treatment capacities recommended by strategies "99," "1983a," and "1983b" relative to those recommended in the 1978 agreement (zero line). Unsubscripted "P, S, and T" represent strategy "99"; otherwise, subscript "a" represents strategy "1983a," "b" represents strategy "1983b," and "ab" represents identical recommendations from strategies "1983a" and "1983b". If a strategy is not shown on the graph, then little or no change in strategy "1978" capacities was recommended.

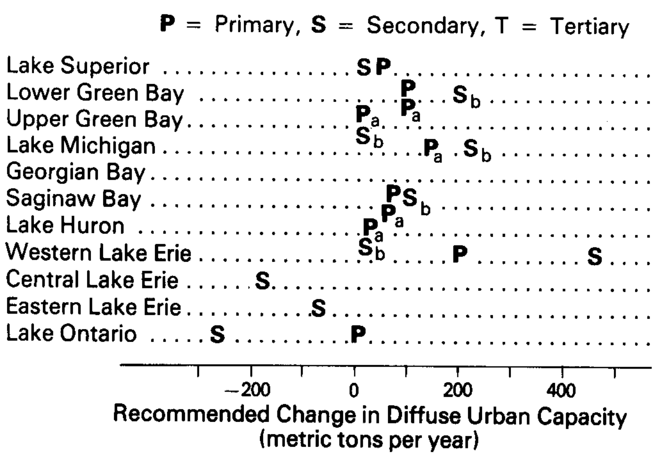

FIG. 8. Changes in diffuse urban treatment capacities recommended by strategies "99," "1983a," and "1983b" relative to those recommended in the 1978 agreement (zero line). Unsubscripted "P, S, and T" represent strategy "99"; otherwise, subscript "a" represents strategy "1983a," "b" represents strategy "1983b," and "ab" represents identical recommendations from strategies "1983a" and "1983b". If a strategy is not shown on the graph, then little or no change in strategy "1978" capacities was recommended.

mation generated by a coupled optimization-uncertainty analysis can suggest a load reduction plan that will be the most cost-effective and successful. With regard to Great Lakes phosphorus management, what have appeared to be reasonable load reduction strategies may no longer be satisfactory when realistic, stochastic conditions are considered.

In reality, management of the Great Lakes is a multi-objective issue: phosphorus management comprises only one facet of an overall problem. Other equally important issues include management of toxic contaminants and fisheries. An alternate question could be posed: would the optimal phosphorus management strategies derived from our analyses be optimal for other management objectives? For instance, would the recommended phosphorus management strategy lead to changes in foodweb structure that would enhance or harm commercial and sports fisheries? Because Great Lakes fisheries depend not only on stocking and removal practices, but also on a food web which is structured in part by phosphorus loadings, it seems reasonable to consider this question. Is is possible that toxic contaminant fate and effects could change if foodwebs and associated particle dynamics are altered as a result of phosphorus load reductions? Because toxic contaminant fate is closely tied to particle behavior and because a significant portion of an organisms toxic contaminant burden can come from its food web, this question should also be considered when devising phosphorus management plans. An enduring goal, then, should be to incorporate such additional relationships into management models so that the Great Lakes can be managed in a multi-objective, holistic manner.

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APPENDIX A

TABLE A-1. ***Phosphorus load reduction capacities[a] that were examined under stochastic phosphorus loading and settling conditions.***

Strategy	Basin	Total Point (MT/yr)	Total Rural (MT/yr)	Total Urban (MT/yr)
1970:	all basins	NC[b]	NC	NC
AVEOPT:	Superior	0	0	0
	Lower Green Bay	781	18	0
	Upper Green Bay	0	4	0
	Michigan	514	98	0
	Georgian Bay	0	0	0
	Saginaw Bay	759	0	0
	Huron	0	60	0
	Western Lake Erie	7,637	400	0
	Central Lake Erie	870	50	0
	Eastern Lake Erie	28	120	0
	Ontario	2,987	160	0
1978:	Superior	375	0	0
	Lower Green Bay	470	0	0
	Upper Green Bay	0	0	0
	Michigan	1,560	0	0
	Georgian Bay	60	0	0
	Saginaw Bay	425	0	0
	Huron	240	0	0
	Western Lake Erie	5,340	600	510
	Central Lake Erie	1,145	140	285
	Eastern Lake Erie	270	155	90
	Ontario	2,630	110	400
1983a[c]:	Superior	375	0	0
	Lower Green Bay	470	9	100
	Upper Green Bay	0	2	7
	Michigan	1,560	49	140
	Georgian Bay	60	15	2
	Saginaw Bay	425	30	75
	Huron	240	65	25
	Western Lake Erie	7,340	600	510
	Central Lake Erie	1,145	140	285
	Eastern Lake Erie	270	155	90
	Ontario	3,840	110	400
1983b[c]:	Superior	375	0	0
	Lower Green Bay	470	9	300
	Upper Green Bay	0	2	18
	Michigan	1,560	54	370
	Georgian Bay	60	25	4
	Saginaw Bay	425	50	175
	Huron	240	120	45
	Western Lake Erie	7,340	600	510
	Central Lake Erie	1,145	140	285
	Eastern Lake Erie	270	155	90
	Ontario	3,840	110	400

Continued

TABLE A-1. Continued.

Strategy	Basin	Total Point (MT/yr)	Total Rural (MT/yr)	Total Urban (MT/yr)
96:	Superior	248	338	20
	Lower Green Bay	505	63	47
	Upper Green Bay	0	23	0
	Michigan	1,175	268	0
	Georgian Bay	27	37	0
	Saginaw Bay	322	243	20
	Huron	133	225	0
	Western Lake Erie	5,405	2,325	442
	Central Lake Erie	680	363	27
	Eastern Lake Erie	237	697	5
	Ontario	1,788	795	35
97:	Superior	345	515	40
	Lower Green Bay	610	75	65
	Upper Green Bay	0	35	0
	Michigan	1,600	335	0
	Georgian Bay	45	45	0
	Saginaw Bay	425	285	40
	Huron	195	270	0
	Western Lake Erie	6,740	2,720	685
	Central Lake Erie	970	535	55
	Eastern Lake Erie	315	945	10
	Ontario	2,135	990	70
98:	Superior	443	692	60
	Lower Green Bay	715	88	83
	Upper Green Bay	0	48	0
	Michigan	2,025	403	0
	Georgian Bay	63	52	0
	Saginaw Bay	528	328	60
	Huron	257	315	0
	Western Lake Erie	8,075	3,115	928
	Central Lake Erie	1,260	708	83
	Eastern Lake Erie	392	1,192	15
	Ontario	2,483	1,185	105
99:	Superior	537	870	86
	Lower Green Bay	818	103	100
	Upper Green Bay	0	64	0
	Michigan	2,450	471	0
	Georgian Bay	77	60	0
	Saginaw Bay	627	368	75
	Huron	318	364	0
	Western Lake Erie	9,410	3,507	1,171
	Central Lake Erie	1,547	884	110
	Eastern Lake Erie	471	1,142	20
	Ontario	2,829	1,381	135

[a]Metric ton amounts represent *additional* capacity needed over that which was present in the mid-1970s.
[b]No capacity over mid-1970s levels.
[c]Addition of level 1 and/or level 2 nonpoint source controls represent recommendations contained in International Joint Commission (1983).